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PROCEEDINGS OF SCIENCE

# Charmless B decays

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I discuss charmless B decays and recent puzzles, mainly in $B \to K\pi$, $B \to \pi\pi$, $B \to K\eta'$ modes. I will briefly summarize the progresses in the theoretical computations and the proposed solutions to these puzzles.

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## 1. Introduction

In this talk, I summarized the puzzles in the charmless hadronic $B$ decays, namely in the comparison of its theoretical prediction and the obtained experimental data. The charmless $B$ decays contain over a hundred of decay channels. Many theoretical attempts have been made to make various relations among those decay channels by using the flavour $SU(3)$ symmetry or by using the quark level diagrams. In more recent years, tremendous efforts have been made for developing new computational techniques based on QCD which allows us to make a theoretical prediction by investigating the dynamics of each diagram. By now, a large number of experimental data for the charmless $B$ decays have been accumulated, which made it possible to test some of the theoretical predictions. We discuss the puzzling phenomena observed recently and proposed solutions for the deviations between theory and experiments.

## 2. Charmless $B$ decays and annihilation contributions

As the experimental measurements of the charmless $B$ decays become more and more precise, it revealed a significantly large direct CP violation. For example, some of the $B \to K\pi$ and $B \to \pi\pi$ modes show over a ten % of direct CP asymmetry. Since the direct CP violation is zero unless there is a strong phase, many theoretical attempts have been made to understand the mechanism of producing a large strong phase. The new development of the QCD based theoretical computation introduced a new source of the strong phase coming from the annihilation diagram. The annihilation diagram is depicted in Fig 1. It has been emphasized that this diagram can become sizable due to the so-called chiral enhancement despite of the fact that it is $1/m_b$ suppressed. Furthermore, the strong phase can be originated by the absorptive part arose from the cuts on the intermediated sates (see Fig 1) [1]. There are a few different approaches of the QCD based computations. While all of them use the $1/m_b$ expansion, the detailed computations are different, which sometimes leads to quite different numerical results. The pQCD approach pointed out that the annihilation phase is the major sources of the strong phase [2, 3]. In the QCD factorization method [4], the annihilation diagram is not calculable due to the end-point singularity and it is simply parameterized by some parameter. The phenomenological study of the QCD factorization shows that this parameter should indeed contain a large imaginary part. On the other hand, the SCET found that the annihilation diagram is calculable while they did not find a large imaginary part [5] . In order to explain the large direct CP violation in charmless B decays, the SCET requires an another source of the strong phase, namely from the charming penguin [6]. The QCD sum rule in [7] also found that the annihilation is calculable but small.

While the existence of the chiraly-enhanced annihilation contribution sounds and is attractive theoretically, a phenomenological identification of this effect is a difficult task since the annihilation diagram occurs together with many of different diagrams in the most of the decay channels. Nevertheless, apart from the large direct CP violation in $B \to PP$ ($P$: pseudoscalar) channel, it has also been argued that the branching ratio predictions for the $B \to VP$ (V: vector) channels are in general too small without the annihilation contributions. Some of the examples are seen e.g. in $B \to \phi K$ decay [9, 8]. Another very attractive argument for the large annihilation contribution is that it may be the solution for the $B \to VV$ polarization problem (see detailed discussion e.g.



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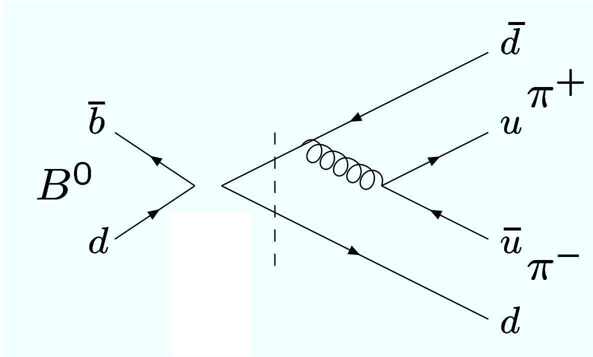


**Figure 1:** Example of the annihilation diagram.

in [10, 11, 12]). The cleanest way to search for the annihilation contribution is to use the pure annihilation processes. Most promising channels might be $B^0 \to K^+K^-$ and $B_s \to \pi^+\pi^-$. These channels can be searched in $B$ factories, Tevatron and also the future experiments, LHCb and SuperB factories. The both pQCD and QCD factorization predict extremely small branching ratio, at the order of $\mathscr{O}(10^{-8})$ [13, 8]. An observation of these channels will have a huge impact on the theoretical understanding of annihilation diagram. It should be mentioned that the pure annihilation channels are actually observed in $B^0 \to D_s^{(*)}K^{+(*)}$ [14]. All of the strangeless $D_s$ and the charmless $B_c$ decays are also pure annihilation processes. The former is already seen with a possible large isospin violation (see e.g. [15, 16] for details). The later is expected to be searched at the LHCb experiment [17].

## 3. Recent progress and new problems in $B \to K\pi$ and $B \to \pi\pi$

There are four and three finals states with different charges in $B \to K\pi$ and $B \to \pi\pi$ processes, respectively. One can make a relation among these decay channels using the quark diagrams, as well as the $SU(3)$ flavour or isospin symmetry. As more and more precise experimental data is available, some deviations from those relations are reported. The so-called $K\pi$ puzzle is one of them: we see a problem in a comparison of two direct CP violations [18]:

$$A^{\rm CP}_{K_-\pi^+} = -0.098^{+0.012}_{-0.011}, \quad A^{\rm CP}_{K_-\pi^0} = -0.050 \pm 0.025. \tag{3.1}$$

The quark level diagrams for these two processes are very similar: dominant penguin contribution ($P$) plus a few tens % of the tree contribution ($T$). The small difference is expected due to the additional contribution to the $B \to K^+\pi^0$ from the electro-weak penguin ($P_{\rm EW}$) and the color-suppresed penguin contribution ($C$). The $P_{\rm EW}$ contribution comes from the $\gamma$ and $Z$ penguin diagram, therefore, it is expected to be a factor of $\alpha_{\rm em}/\alpha_s$ suppressed comparing to the gluon penguin $P$. The $C$ contribution is also supposed to be suppressed by the color factor with respect to the sub-dominant $T$ contribution (at the scale $\mu = M_W$, $T/C \simeq 1/N_c$). As a result, the sum of these two additional contributions are, *a priori*, a minor correction. Thus, the difference found by the experiment, Eq. (3.1), came as a surprise and various theoretical attempts to understand this puzzling phenomena

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have been carried out. First thing one would try is the re-evaluation of the $P_{\rm EW}$ and $C$ contributions. On the other hand, since these contributions appear to the other $B\to K\pi$ and $B\to\pi\pi$ decay channels, it is essential to examine simultaneously the consequence of changing the $P_{\rm EW},C$ contributions to these channels. For this reason, various global fits among $B\to K\pi$ channels have been performed including possible effects beyond SM [19, 20, 21].

As a matter of fact, there have also been another kinds of puzzles in the $B\to K\pi$ and $B\to\pi\pi$ channels. For the $B\to\pi\pi$ mode, various branching ratios and CP violations have been measured [18]:

$$\overline{Br}(B^0\to\pi^+\pi^-)=(5.16\pm0.22)\times10^{-6},\quad \overline{Br}(B^+\to\pi^+\pi^0)=(5.59^{+0.41}_{-0.40})\times10^{-6} \tag{3.2}$$

$$\overline{Br}(B^0\to\pi^0\pi^0)=(1.55\pm0.19)\times10^{-6} \tag{3.3}$$

$$S_{\pi^+\pi^-}=-0.65\pm0.07,\quad A_{\pi^+\pi^-}=-0.38\pm0.06 \tag{3.4}$$

$$A_{\pi^0\pi^0}=0.06\pm0.05,\quad A_{\pi^0\pi^0}=0.43^{+0.25}_{-0.24} \tag{3.5}$$

where $\overline{Br}$ represents the CP averaged branching ratio. By fitting these measurements to the theoretical parameterization based on the diagram (namely the complex parameters $T,C,P,P_{\rm EW},A$...) and the CKM matrix parameter $\gamma/\phi_3$ shows a clear sign of large $C$ contribution ($C/T$ to be order one [24, 23, 22]). Various theoretical ideas have been proposed to explain the dynamics behind such a large $C/T$ ratio. In [25], it is argued that the large $C/T$ is attributed to the spectator-scattering contributions of the QCD factorization. The most recent result of pQCD shows that there is an extra soft contribution for the pseudoscalar final states, namely for $\pi$ and $K$, which indeed enhances the color-suppressed tree contribution [26]. Important finding is that in this way, $B\to\pi\pi$ branching ratio is enhanced without modifying the $B\to\rho\rho$ branching ratio for which theory prediction agrees with the experimental data relatively well. Another interesting possibility to explain the large $C/T$ is the final-state interaction (see e.g. [24]). Recently it was shown that the contribution from the $B\to\rho\rho$ intermediated contribution can indeed enhance the $C/T$ ratio of $B\to\pi\pi$ channel significantly [27].

There was another puzzle related to the branching ratio of $B\to K\pi$ in the ratio of:

$$R_c = 2\frac{\overline{Br}(B^+\to K^+\pi^0)}{\overline{Br}(B^+\to K^0\pi^+)}=1.1\pm0.07 \tag{3.6}$$

$$R_n = \frac{1}{2}\frac{\overline{Br}(B^0\to K^+\pi^-)}{\overline{Br}(B^0\to K^0\pi^0)}=0.99\pm0.07 \tag{3.7}$$

These two variables are equal at the isospin limit, moreover the correction to it was expected to be $R_n>R_c$. Several years ago, the $R_n$ value was even smaller and it was found that a large negative value of $R_n-R_c$ would require a new physics contribution which breaks CP on top of isospin [23]. Such a contribution can be produced by the electro-weak penguin with new physics particle (e.g. charginos in the SUSY models [28]) in the loop. A further improvement in the experimental precision will shed light on the new physics search in this decay channel.

To conclude, in comparison of the theoretical prediction and the obtained experimental data on $B\to K\pi$ and $B\to\pi\pi$, we see a couple of puzzling phenomena. Theoretical understanding within and beyond SM has been attempted. To clarify if this is a new physics, a more precise data on these channels would be most useful. In particular, the neutral channels, $B^0\to K^0\pi^0$ and $B^0\to\pi^0\pi^0$ are very important to complete many of the theoretical analysis.



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## 4. The large branching ratio of $B \to K\eta'$ resolved?

First observations of a large branching ratio for $B \to K\eta'$ triggered numerous theoretical investigations within and beyond the standard model. The latest average of the available experimental data [18]:

$$Br(B^0 \to K^0\eta') = (64.9 \pm 3.1) \times 10^{-6}, \quad Br(B^+ \to K^+\eta') = (70.2 \pm 2.5) \times 10^{-6} \tag{4.1}$$

definitely confirms a sizable excess of $\eta'$ compared with $\pi^0$, $Br(B^0 \to K^0\pi^0) = (9.8 \pm 0.6) \times 10^{-6}$, $Br(B^+ \to K^+\pi^0) = (12.9 \pm 0.6) \times 10^{-6}$, and $\eta$, $Br(B^0 \to K^0\eta) = (1.0 \pm 0.3) \times 10^{-6}$, $Br(B^+ \to K^+\eta) = (2.7 \pm 0.3) \times 10^{-6}$. The SU(3) relation assuming the pseudoscalar mixing angle of $\theta_p \simeq -19.5^\circ$ is derived [29]:

$$Br(K^+\eta') : Br(K^+\eta) : Br(K^+\pi^0) = 3 : 0 : 1 \tag{4.2}$$

The null branching ratio of $Br(K^+\eta)$ comes from the fact that the $b \to s s\bar{s}$ and $b \to s d\bar{d}$ penguin contribute destructively for the $K\eta$ final state and in particular, it becomes zero when we use the above $\theta_p$ where quark content of $\eta$ is $\eta = (u\bar{u} + d\bar{d} - s\bar{s})/\sqrt{3}$. On the other hand, the large observed branching ratio of $B \to K\eta'$ comparing to $B \to K\pi$ is still questionable. Here we summarize the theoretical progresses in order to explain the large branching ratio of the $B \to K\eta'$.

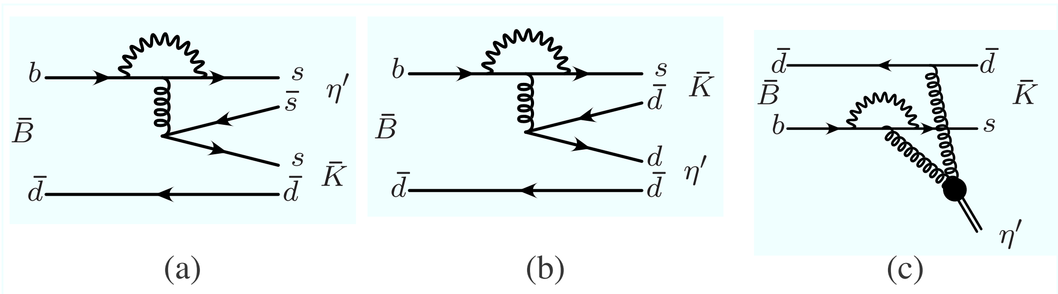


**Figure 2:** Main Feynman diagrams for the $B \to K\eta'$ decay.

The main contributions come from three kinds of diagrams: a) $b \to s s\bar{s}$ penguin (Fig 2(a)), b) $b \to s d\bar{d}$ penguin (Fig 2 (b)) and c) two gluons, one from $b \to sg$ and one from the spectator, fusing into $\eta'$ (Fig 2(c)). The diagram a) produces the dominant contribution in general since the $s\bar{s}$ is the largest component of $\eta'$ (e.g. for $\theta_p \simeq -19.5^\circ$, $\eta' = (u\bar{u} + d\bar{d} + 2s\bar{s})/\sqrt{6}$). In the naive factorization, this diagram is proportional to the $\eta'$ decay constant or density matrix. The theoretical predictions for these quantities have been studied in the framework of the effective Lagrangian. It has been shown that the density matrix is, in particular, enhanced due to the U(1) anomaly contributions and it can largely break the SU(3) relation mentioned above [30]. There is one subtlety for the computation of the a) contribution. The gluon penguin contribution leads to four type of operators $O_{3,4,5,6}$. For the amplitudes for the processes with SU(3) singlet meson in the final state, the combination of the Wilson coefficient $a_{3(5)}(\mu) \equiv C_{3(5)}(\mu) + C_{4(6)}(\mu)/3$ appears, in addition to the dominant contribution $a_{4(6)}(\mu) \equiv C_{4(6)}(\mu) + C_{3(5)}(\mu)/3$ which appears both for the octet and the singlet final states. Important thing is that the sign of $a_{4(6)}(\mu)$ and $a_{3(5)}(\mu)$ contributions turn

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out to be opposite in $B \to K\eta'$ thus, $a_{3(5)}(\mu)$ terms partially cancel the dominant $a_{4(6)}(\mu)$ contribution. The $\mu$ dependence of $a_{3(5)}(\mu)$ is rather strong (stronger than $a_{4(6)}(\mu)$) and the cancellation is more emphasized at the lower value of $\mu$. This effect leads to a different theoretical predictions depending on the QCD models applied. In particular, the pQCD predictions end up to be in the smaller side since the mean value of the renormalization scale obtained in the pQCD computation is rather low [31]. A NLO computation would moderate such strong dependence on $\mu$ and it may help to reduce this cancellation (this is also confirmed in [32]). For the figure b), the main issue is the estimate of the $B \to \eta'$ form factor. Recently, the $B \to \eta'$ form factor is re-evaluated in the QCD sum rule [33]. There is a new experimental result for the semi-leptonic $B \to \eta' l\nu$, which will also help to determine the $B \to \eta'$ form factor once the experimental errors will be reduced [34, 35]. Some enhancement has been found and e.g. in the SCET estimate of the $B \to K\eta'$ branching ratio, one of the contributions to the form factor (annihilation-charming penguin) plays a main role to explain the large branching ratio [36]. The diagram in figure c) is possible only for the $SU(3)$ singlet mesons such as $\eta$ and $\eta'$. The several theoretical evaluations of this diagram have been made and they show a small enhancement of the branching ratio [31, 32].

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